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Title: Application of muon tomography to fuel cask monitoring

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Application of muon tomography to fuel cask monitoring*

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14 May 2018

Long term monitoring of spent fuel stored in dry cask storage is currently achieved through the use of seals and surveillance. Muon tomography can provide direct imaging that may be useful in cases where what is known as continuity of knowledge (COK) has been lost using the former methods. Over the past several years a team from Los Alamos National Laboratory has been studying the use of muon scattering and stopping to examine spent fuel in dry cask storage. Data have been taken examining a Westinghouse MC-10 spent fuel cask partially loaded with Surry 15x15 PWR fuel assemblies located at the Idaho National Laboratory. The data demonstrate that muon scattering radiography can detect the missing fuel assemblies in this cask.
Model, validated by this data, shows that tomographic reconstructions of the fuel can be obtained in relatively short exposures. Model fitting algorithms have been developed for dealing with data sets with limited angular that appear to work well. The data, modeling, and reconstruction methods developed during this work will be presented. Burnup fractions can provide fuel cask signatures.

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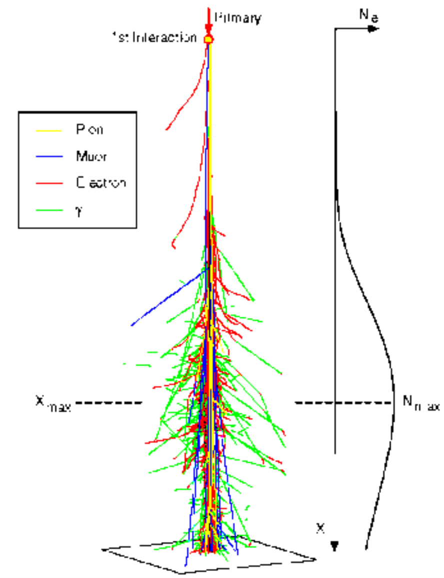
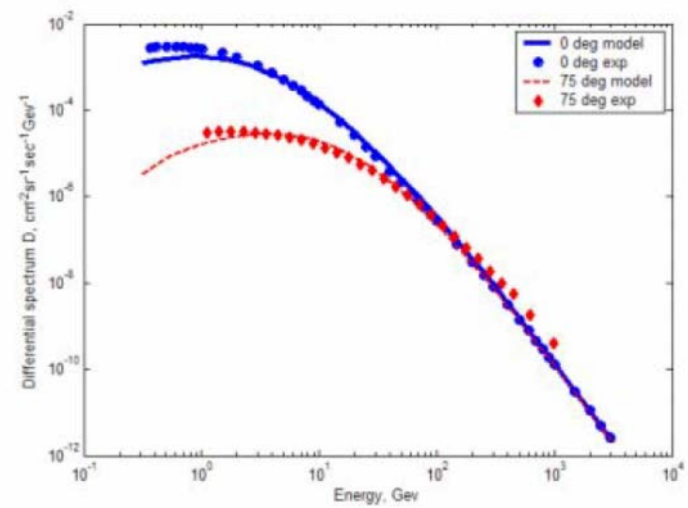
What are Cosmic rays

- Mean energy of a few GeV, highly penetrating.
  - Muons interact only through Coulomb and weak forces.
  - $dE/dx \approx 2.0$ MeV/g/cm^2.
  - 4 GeV muons have a range of ~7 m in concrete.
- Muon flux.
  - 10,000 muons/m^2/min at the earth's surface. 1/thumbnail/minute
- Strong angular dependence.
  - Muon flux roughly scales with $\cos^2\theta$ where θ is the zenith angle.





Energy spectrum of cosmic-ray muons.

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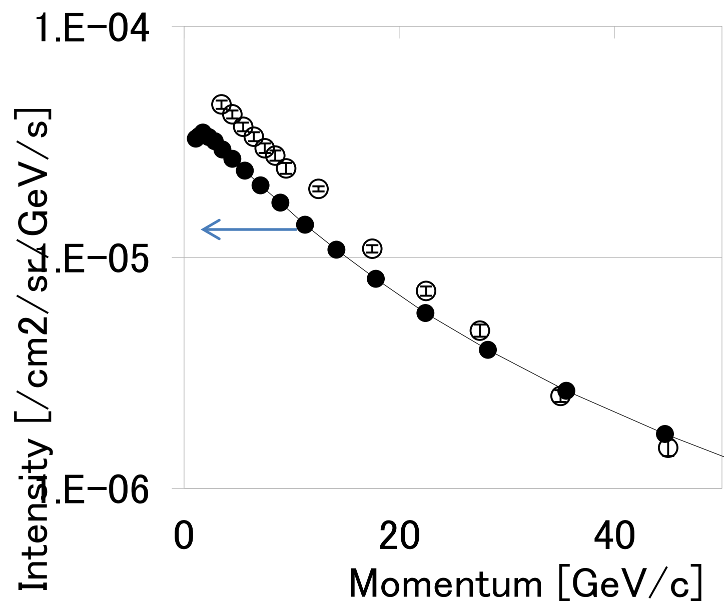
Energy Loss

$$\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln(\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



Multiple Scattering

$$\frac{dN}{d\theta} = \frac{1}{2\pi\theta_0^2} e^{-\frac{\theta^2}{2\theta_0^2}} d\Omega$$

$$\theta_0 = \frac{14.1}{p\beta}\sqrt{\frac{L}{X_0}}$$

$$X_0 = \frac{K}{A}\left\{Z^{2}\left[L_{rad} - f(Z)\right] + ZL'_{rad}\right\}$$

	dx/dE cm/GeV	x cm
Reactor Core	731.9	8.7
Concrete	254.1	15.8
Fe	88.4	9.5
water	502.5	36.0

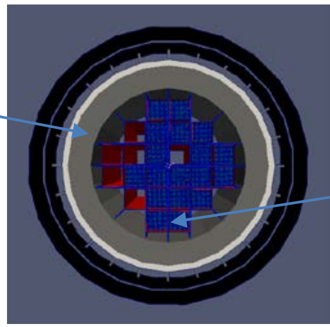
Our detector: the Mini Muon Tracker

- 576 drift tubes arranged in X and Y layers
- Trackers size: 120 cm x 120 cm x 60 cm

Gas mixture: 47.5% Ar, 42.5% CF_4, 7.5% C_2H_6, 2.5% He
Al tubes, gold-plated anode wire, 30-µm diameter

Fuel cask tomography

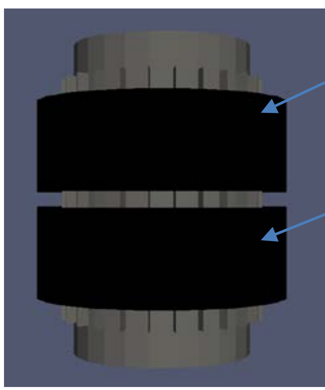
Top View



Cask wall (steel)

Fuel slots

Side view

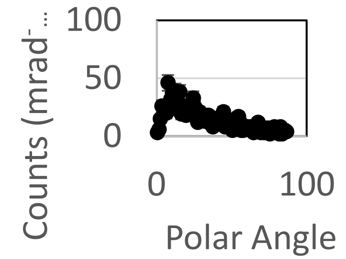


Input detector

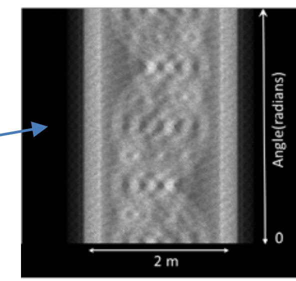
Output detector

- Measure or model trajectory through the cask with Geant.
- Construct a histogram of scattering angle for each pixel in a sinogram. Integrate in the vertical direction.
- Fit the scattering angle distribution to get the areal density using the calibrated multi group method. Enter into a 2-d histogram.
- Apply filtered back projection tomography to obtain a cross section of scattering length density. Empty slots are visible with 20 σ significance

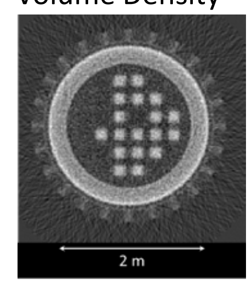
Multi-group fit for a typical sonogram pixel



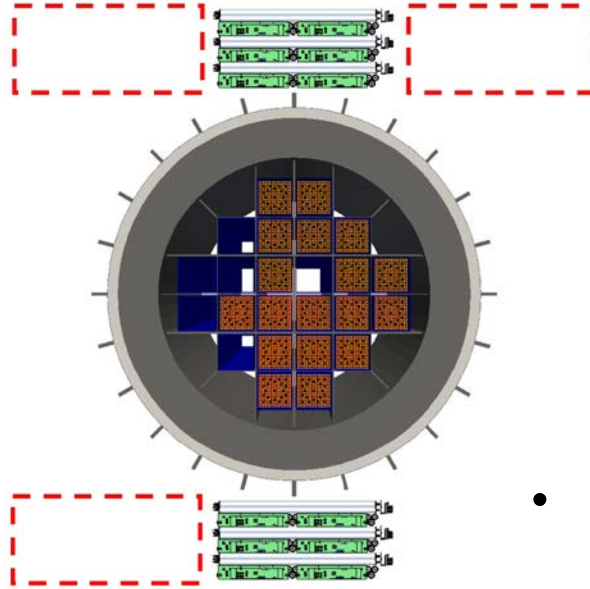
Sinogram

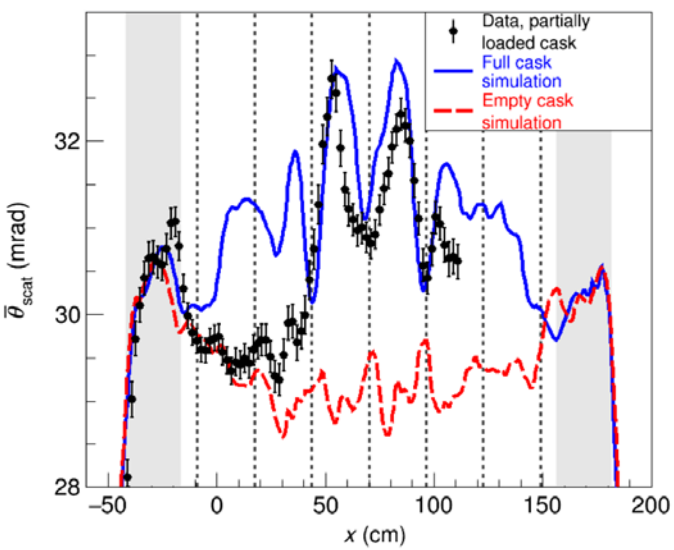


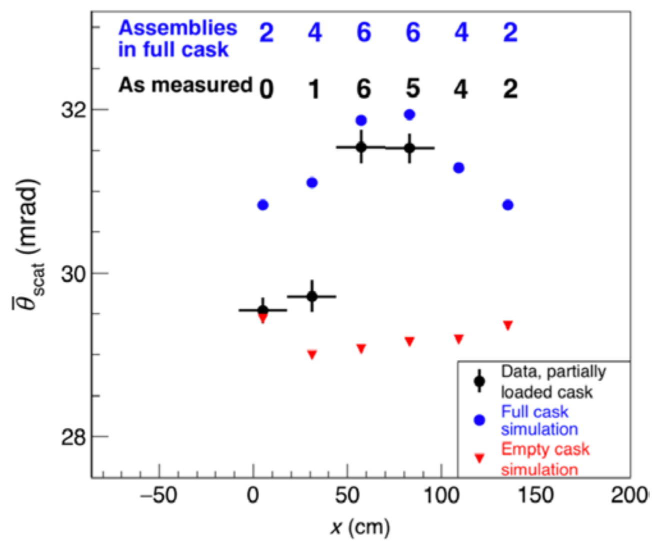
Volume Density



Data from INL run (MC10 cask)







- Exposure 90 days (10 days/position)
- Detector area ~1×1 m^2
- Efficiency <50%
- Demonstrate missing fuel with high reliability
- Much room for improvement

Durham J, Poulson D, Bacon J, Chichester D, Guardincerri E, Morris C, et al. Verification of Spent Nuclear Fuel in Sealed Dry Storage Casks via Measurements of Cosmic-Ray Muon Scattering. Physical Review Applied. 2018;9(4):044013

Model fitting can reduce the amount of data required

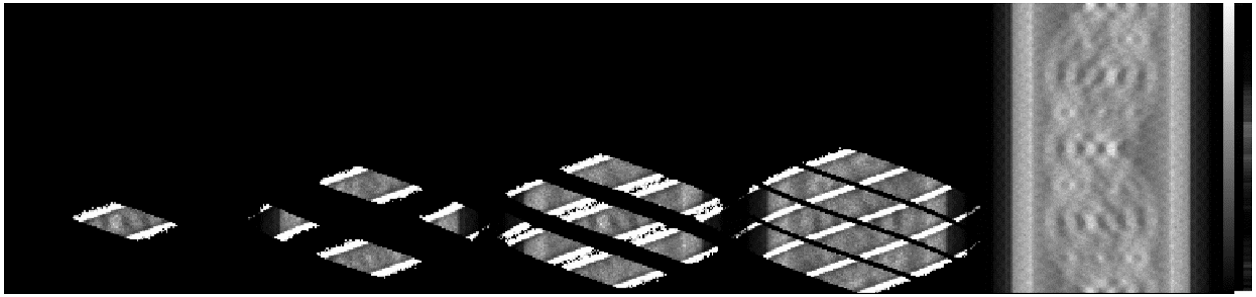


Figure 1) from left to right n=1,2,3,4 and the full data set.

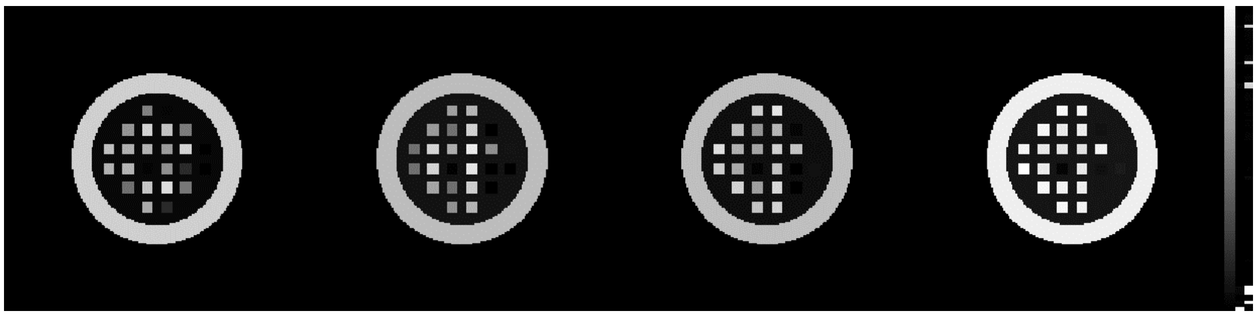


Figure 1) Densities obtained from the partial data sets compared to the full data set. These are for n=2,3,4 and full from left to right. The n=1 data is under constrained without further constraints, since there is no data for the cask wall.

then

$$\rho_k = \sum_i p_{ki} a_i . \qquad 1$$

One can form a X^2 as

$$\mathrm{X}^2 = \sum_k (\rho_k - y_k)^2 , \qquad 2$$

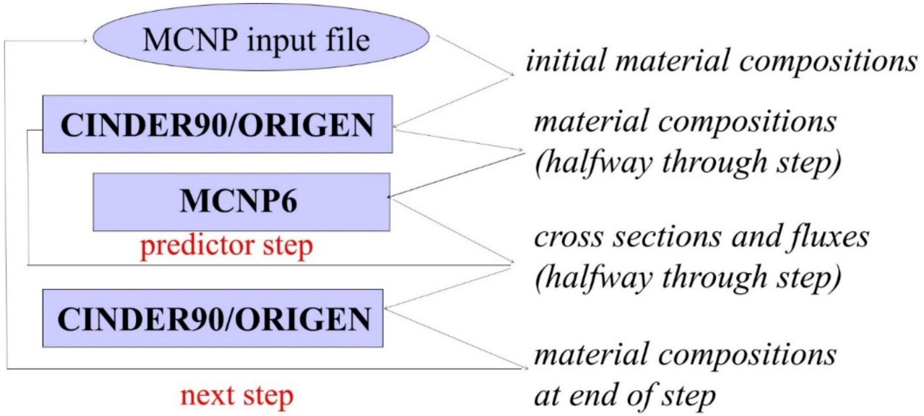
where y_k is the measured sinogram. The index k runs over both angles and position in the sinogram. The a's are found by solving:

$$\frac{d\mathrm{X}^2}{da_j} = 0 = \sum_k 2\left(\sum_i p_{ki} a_j - y_k\right) p_{kj} . \qquad 3$$

Poulson DC, Durham JM, Guardincerri E, Morris C, Bacon JD, Plaud-Ramos KO, et al. Application of filtered back projection to muon radiography for imaging dry storage casks. Nuclear Instruments and Methods in Physics Research Section A, Accelerators, Spectrometers, Detectors and Associated Equipment. 2017;842(LA-UR--16-21971)

Burnup Simulations

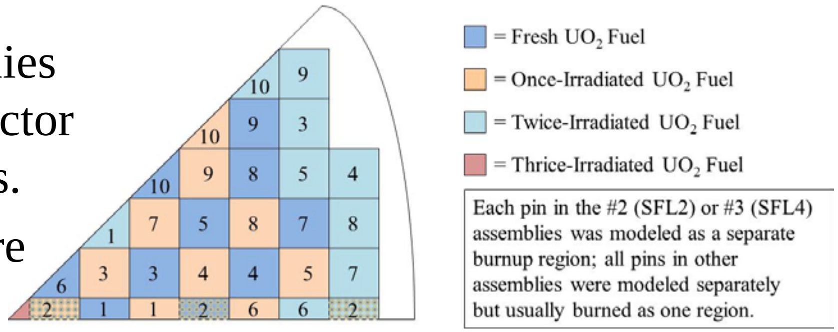
- Spent fuel libraries (SFL) were generated using *Monteburns* to represent assymetric irradiated fuel assembly compositions.*
- *Monteburns* links Monte Carlo transport code MCNP to an isotope generation and depletion tools such as CINDER or ORIGEN provide both time- and energy-dependent system parameters.
- MCNP uses continuous-energy cross sections (interpolated from ENDF data) to provide accurate probabilities of interactions at all energies.
  - Scatter
  - Fission
  - Capture

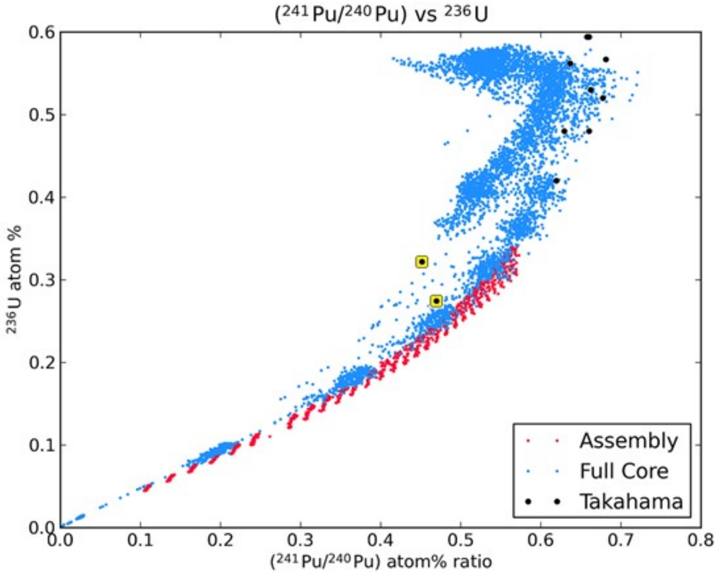


*Trellue, H. R. Galloway, J. D., Fischer, N. A., and Tobin, S. J., "Advances in Spent Fuel Libraries," Institute of Nuclear Materials Management conference, (2013).

Pressurized Water Reactor (PWR) Simulations

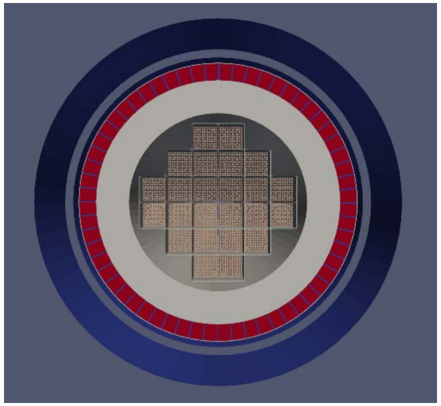
- Individual pins in PWR assemblies were modeled in a 1/8th core reactor simulation with three fuel cycles.
- Results for two model types were compared to measured values:
  - 1/8th PWR Core (reflected to simulate full core) in blue, and
  - Assembly-level in red.
- Measured data from Takahama reactor in Japan are shown in black/yellow.*

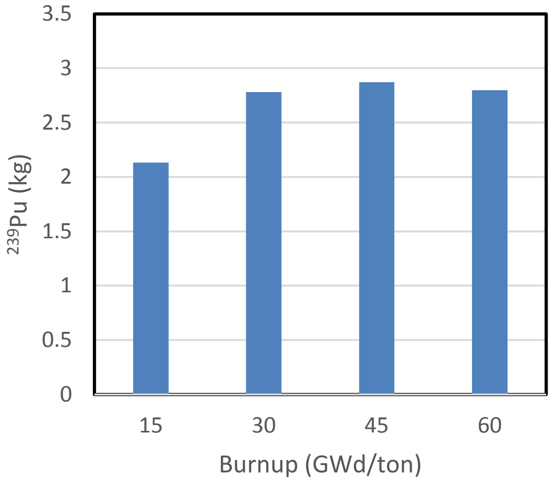




*M. Kurosawa, Y. Naito, H. Sakamoto, and T. Kaneko, "The Isotopic Compositions Database System on Spent Fuels in Light Water Reactors(SFCOMPO)," JAERI-Data/Code 96-036, Japan Atomic Energy Research Institute (February 1997) and OECD Nuclear Energy Agency Spent Fuel Composition Database at: *https://www.oecd-nea.org/sfcompo/.*

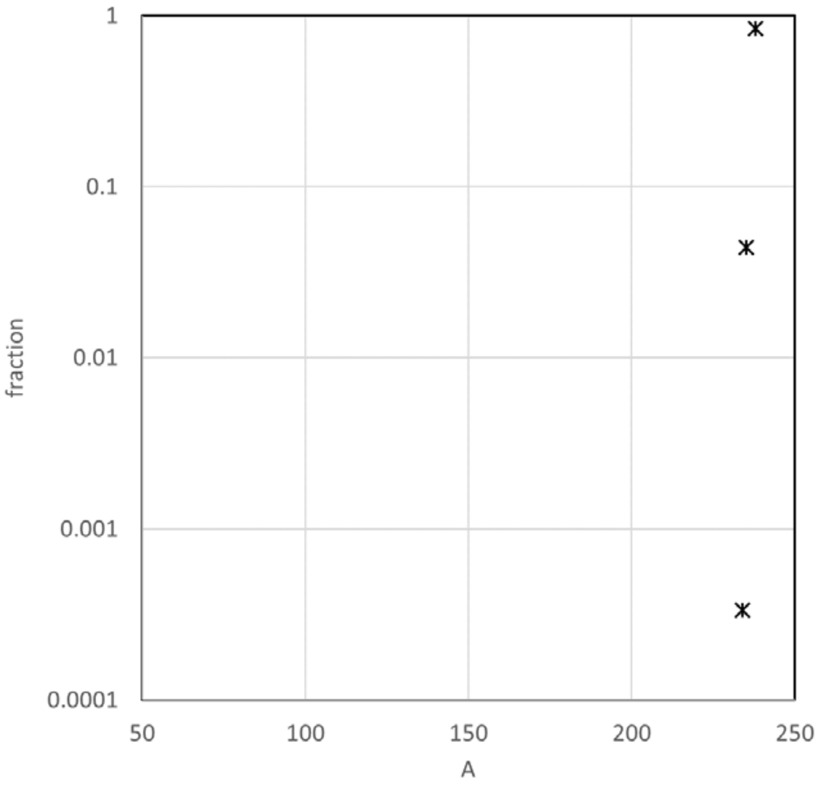
TN-24P fuel burn up and diversion simulations





1 SQ=8 kG Pu ≈4 bundles

Can muon radiography fingerprint a fuel cask?
Can diversion of 1 SQ of Pu be detected?



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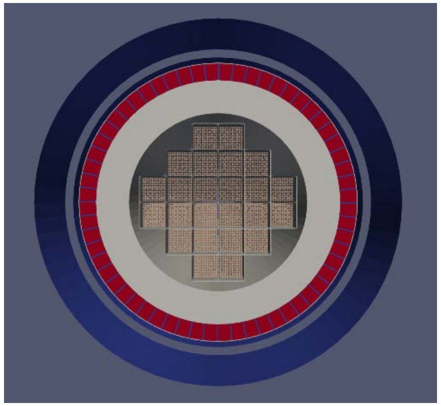

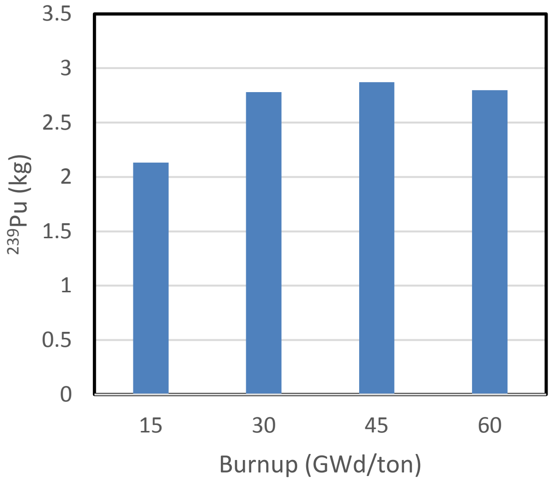

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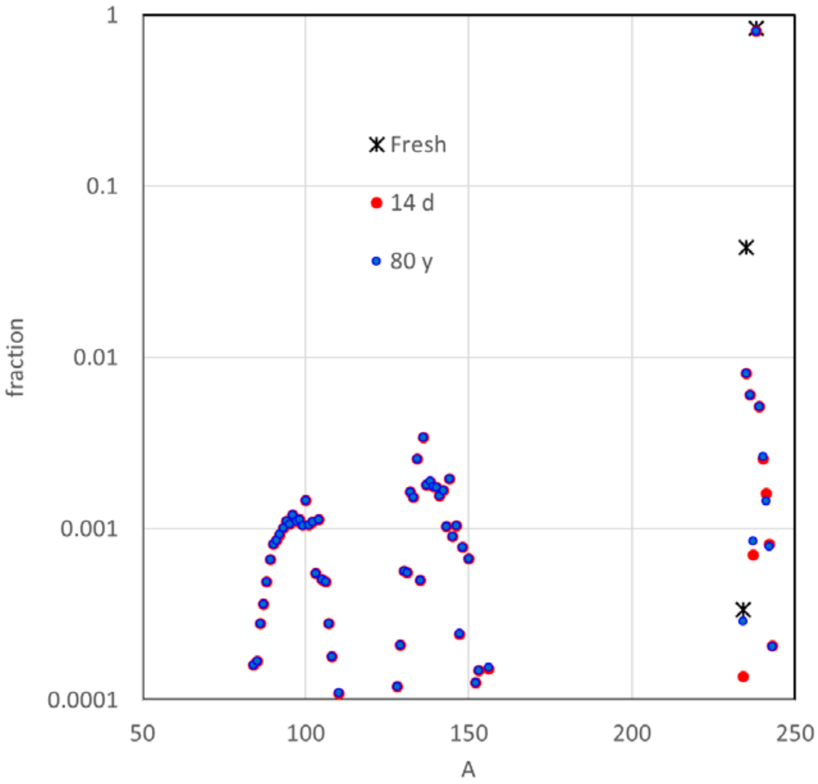
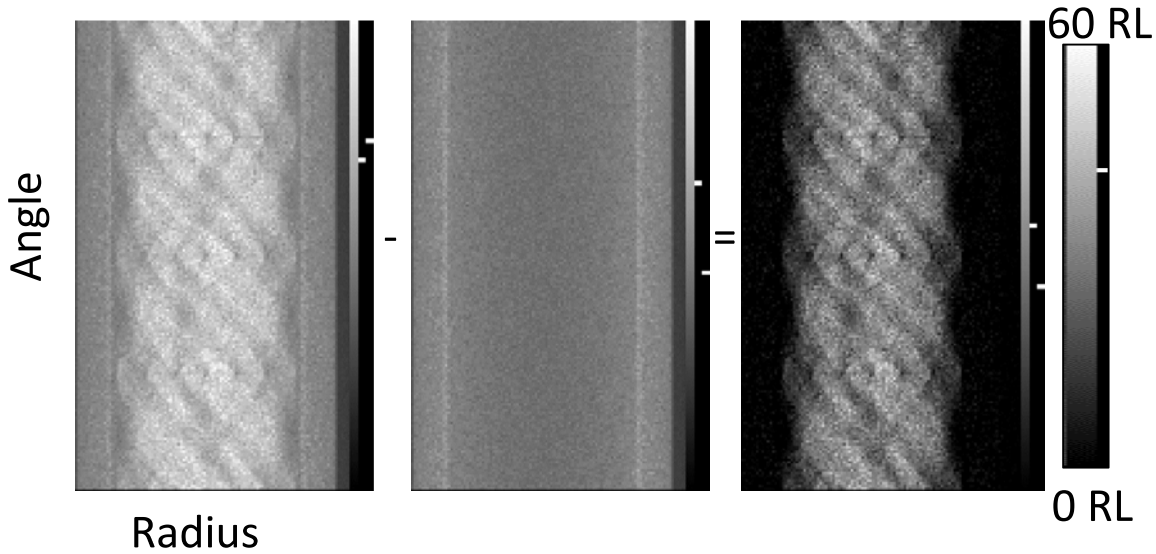
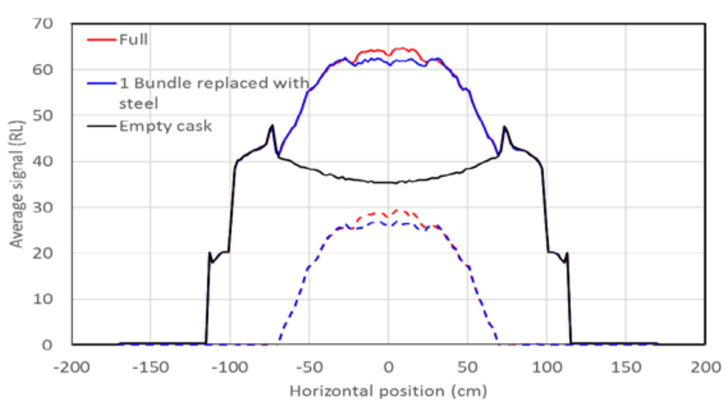
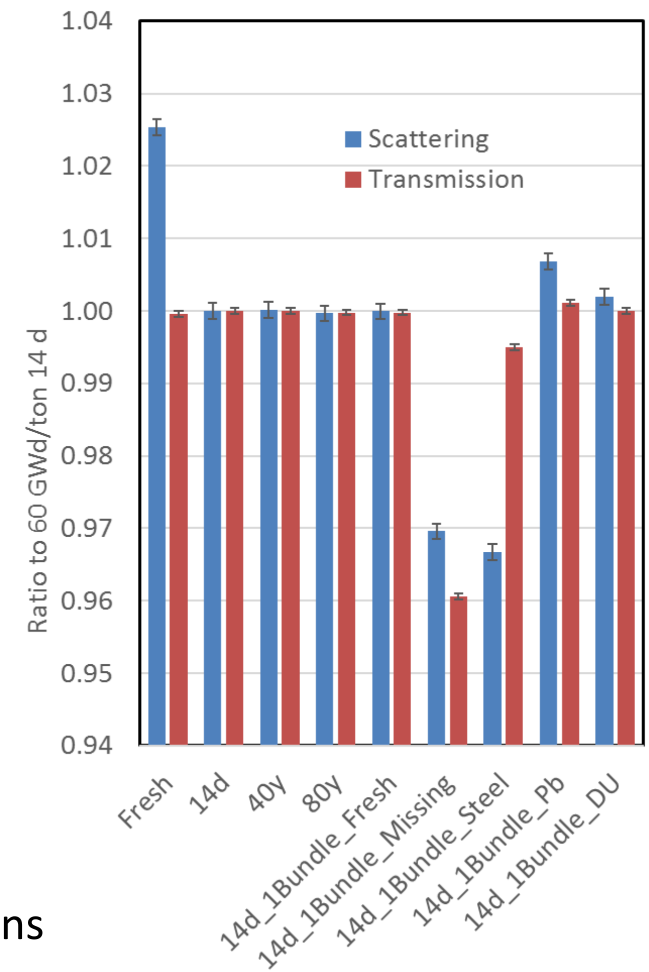


TN-24P PWR spent-fuel dry storage cask; signatures of diversion

60 GW days/ton one bundle replaced with iron





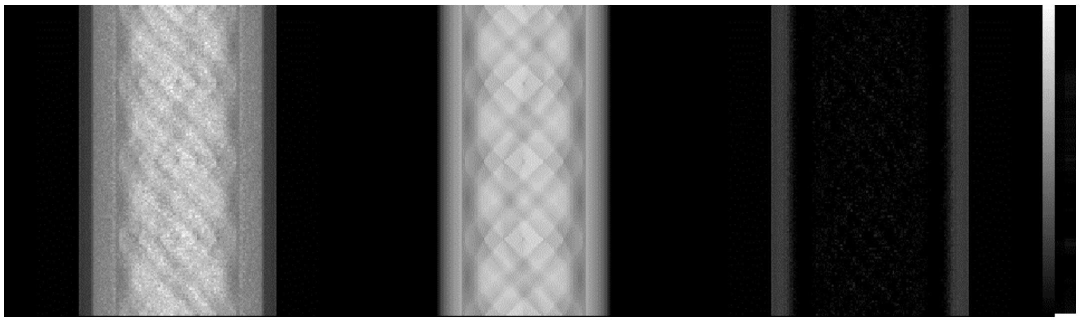


2×10^{8} muons
~7 days

Model fitting (scatter)

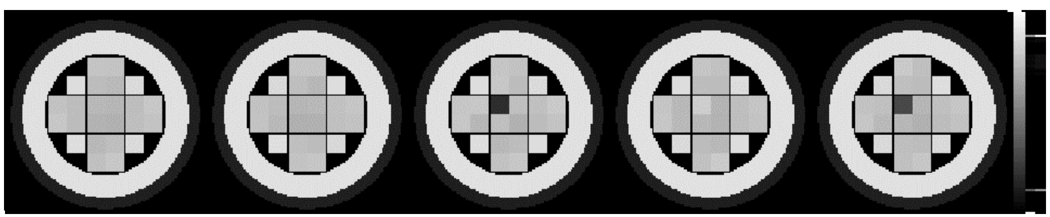
1 fuel bundle replaced with steel

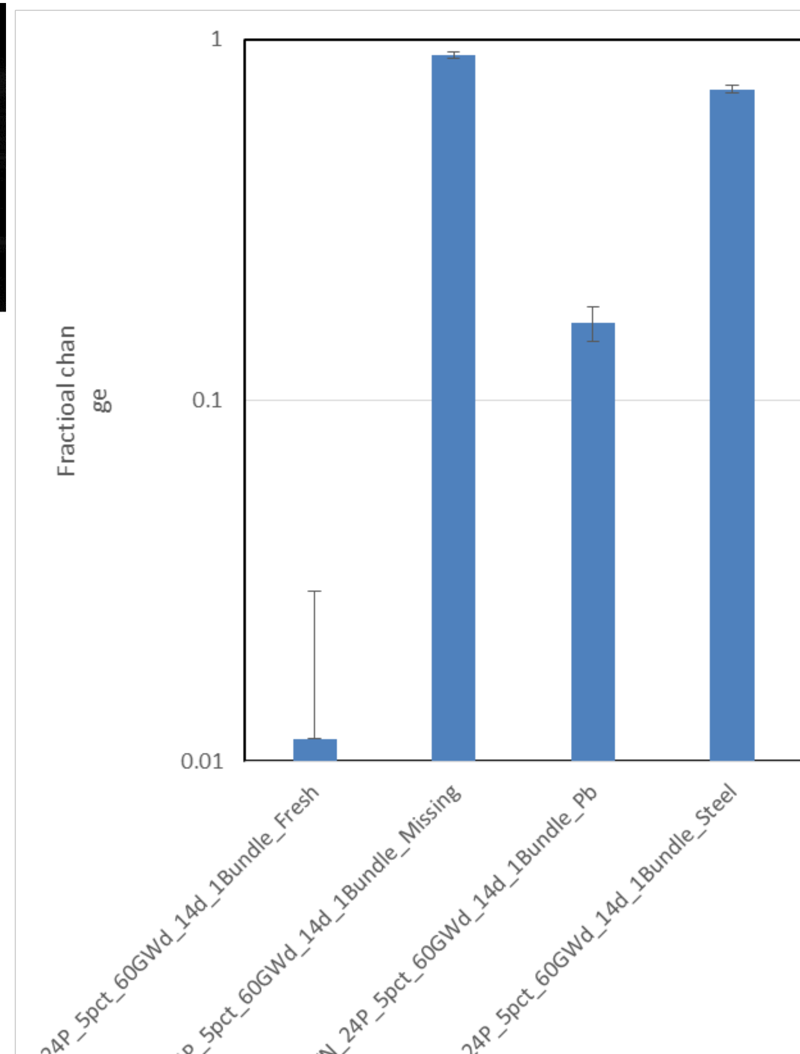
data fit difference



Densities

14 d fresh missing lead Steel



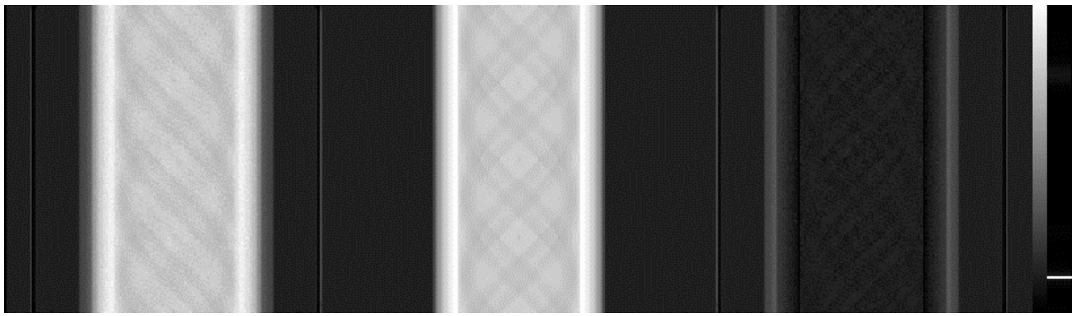


Missing and replaced fuel bundles can be detected.
Sensitivity may improve with improved model.

Model fitting (transmission)

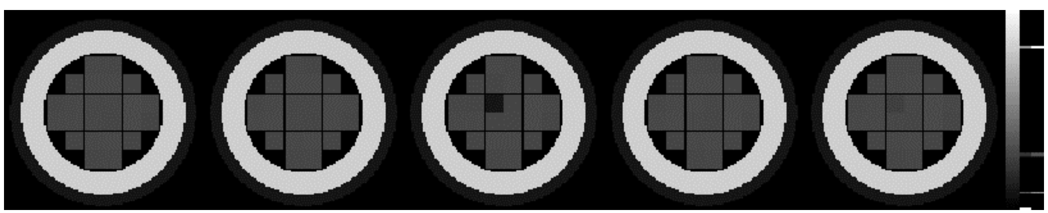
1 fuel bundle replaced with steel

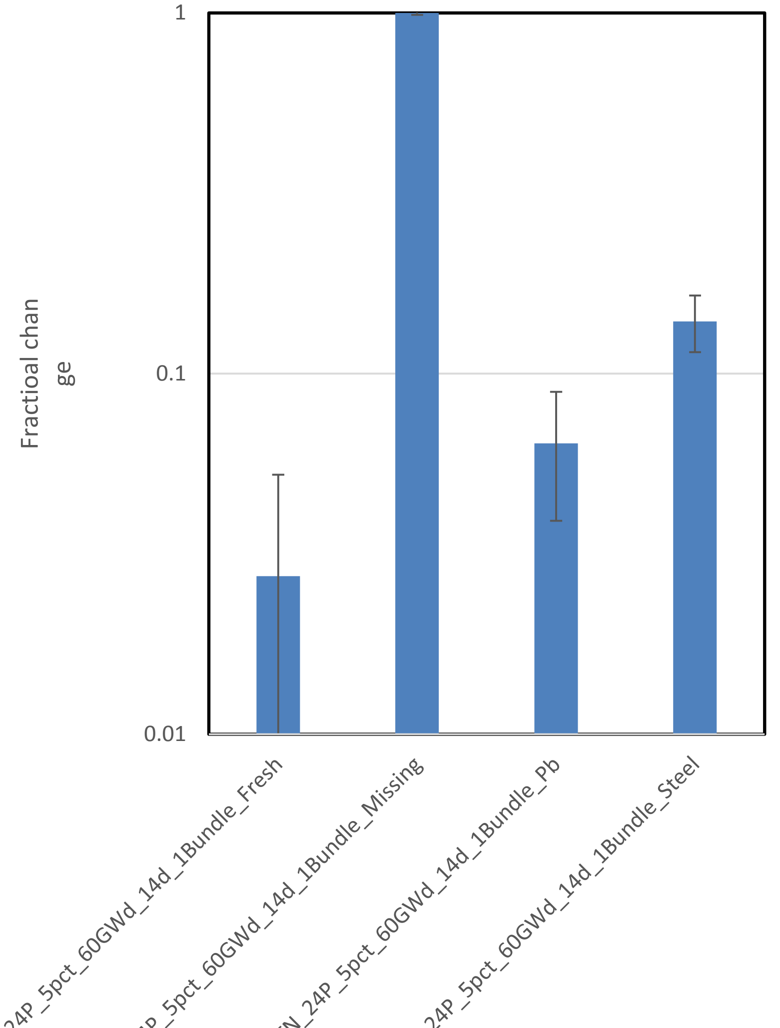
data fit difference



Densities

14 d fresh missing lead Steel





Missing and replaced fuel bundles can be detected.

Sensitivity may improve with improved model.

Path forward

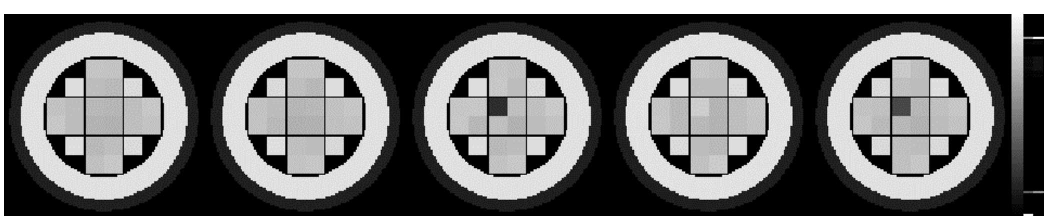
Proposal to NA22
- Larger detectors
  - $R=2^2\times1.5^2$
- Currently being commissioned in Los Alamos

Summary

- Both transmission and scattering radiography can detect many diversion scenarios
- Stopping has more statistical precision of missing fuel bundles
- Scattering has much more sensitivity to burnup fraction and replacement materials

Densities

14 d fresh missing lead Steel



Scatter

	Signal	Δsignal	SD
Fresh	0.01	0.01	0.77
Missing	0.90	0.01	60.24
Pb	0.16	0.01	10.95
Steel	0.73	0.01	48.49

Transmission

	Signal	Δsignal	SD
Fresh	0.03	0.03	1.06
Missing	1.01	0.03	39.23
Pb	0.06	0.03	2.48
Steel	0.14	0.03	5.41